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AN IMPROVED METHOD OF COMPENSATING WHOLE BODY PLETHYSMOGRAPHS.

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The frequency response of a volume plethysmograph may be improved by pressure compensation. The optimal level of compensation is a variable, however, depending upon spirometer characteristics and subject size. The Fast Fourier Transform allows the rapid determination of a transfer function describing the plethysmograph response in terms of amplitude and phase changes over a range of frequencies. The transfer function presents in an easily interpretable format the information necessary to adjust compensation gains and describe the effect of the plethysmograph system on input signals.

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AN IMPROVED METHOD OF COMPENSATING WHOLE BODY PLETHSMOGRAPHS

USING FAST FOURIER TRANSFORM TECHNIQUES

INTRODUCTION

The whole body plethysmograph, or body box, has earned a reputation among respiratory physiologists and pulmonary technicians as an ingenious, useful, but rather complicated tool. It allows the measurement of airway resistance, and provides an alternative to simple spirometry for measuring changes in lung volume. Much of the information gleaned from a body box is obtained indirectly, by the compression or movement of air within the box. Between the movement of gas within the body and the signal emanating from the box lies much room for error. To obtain a faithful representation of the respiratory event, a body box must be "tuned" to obtain an optimal frequency response, such that both the addition and subtraction of unwanted signals is minimized.

The following is a description of a precise and relatively simple means for optimizing the characteristics of pressure-compensated body boxes, one of the several types of boxes available. Pressure compensation is a means of improving the frequency characteristics of a body box (Van de Woestijen and Bouhuys 1969) and the method of optimizing that compensation is the Transfer Function (TF) obtained by a Fast Fourier Transform (FFT).

METHODS

The Fast Fourier Transform is a mathematical algorithm which allows periodic, time-based signals to be examined in the frequency domain (Brigham 1974). It has been used in the analysis of transient, nonstationary biomedical data such as EEG's and EKG's (Yoganathan, Gupta and Corcoran 1976), and for the determination of respiratory impedance (Landser, Nagels, Demedts, Billiet, and Van de Woestijne 1976; Michaelson, Grassman and Peters 1975). As used in the current applicaton, the FFT derived transfer function characterizes the impedance of the plethysmographic system.

The most convenient means of obtaining an FFT is from a dedicated, special purpose FFT analyzer. Alternatively, a minicomputer can be programmed to perform the same tasks (Jackson and Vinegar 1979). Regardless of how it is obtained, the frequency spectrum is usually expressed as a power spectrum (G_{AA}), a representation of the signal strength or power residing in each frequency contained within the original time based signal A (Fig. 1).

$$G_{AA} = \overline{S_A \cdot S_A{}^*} \quad \text{where } S_A = \mathcal{F}[A(t)] \text{ or the instantaneous spectrum.} \tag{1}$$

($S_A{}^*$ is the complex conjugate of S_A).

FFT analyzers are often capable of determining the spectral characteristics of two signals (A and B) simultaneously, and relating them to each other (a cross spectrum, G_{AB}).

$$G_{AB} = \overline{S_B \cdot S_A{}^*} \tag{2}$$

This ability is especially useful in plethysmography as it is necessary to know how the signal leaving a body box relates to the incoming signal (chest movements of a subject). The complex ratio of those signals is called the transfer function (H_{AB}), and contains information on magnitude and phase changes over a given range of driving frequencies (Figs. 2, 3).

$$H_{AB} = \frac{G_{AB}}{G_{AA}} \tag{3}$$

While knowledge of signal magnitude is required for calibration of volume changes within the box, phase information is required for interpretation of pulmonary resistance and compliance measurements, where a volume or flow signal is compared to a supposedly in phase pressure signal.

INPUTS

Input signals containing a range of frequencies (McCall, Hyatt, Noble, and Fry 1957) may be generated by random noise (Michaelson, Grassman and Peters 1975), impulses (Landser, Nagels, Demedts, Billiet, and Van de Woestijne 1976), or swept sine. Loudspeakers are adaptable to all forms of box excitation, whereas mechanical pumps are limited to swept sines. No single method seems significantly better than the others, although swept sines may yield smoother transfer function curves. Loudspeakers are more amenable to rapid, automated testing of box frequency characteristics, especially since some FFT analyzers provide digital pseudo-random noise outputs to drive the speakers.

An accurate representation of the box input signal is required for a transfer function, but accuracy is sometimes elusive. The displacement of a speaker cone or piston may be followed by an attached linear variable differential transformer (LVDT), or at higher frequencies by an integrated accelerometer signal, as long as care is taken to prevent resonance of the transducer assembly itself. Jackson and Vinegar 1979 have designed a special chamber which monitors speaker cone displacement by the pressure changes in a closed container. A similar method can be used to monitor pump motion if reciprocating pistons are used, one piston to generate a box signal and one to pressurize a small container. The sinusoidal pressure changes occurring in the container can then be used as a reference signal.

SPIROMETER RESPONSE

Volume compensation plethysmographs typically respond over a range of frequencies in the following manner: 1) at low frequencies an input volume change is faithfully reproduced; 2) at middle frequencies the spirometer begins to resonate, falsely accentuating amplitude changes; 3) at higher frequencies, the spirometer cannot keep up with the input, and thus amplitude and phase characteristics of the output are degraded. Two means exist for linearizing the spirometer response--one is damping (Van de Woestijne and Bouhuys 1969) (Fig. 2) and the other is pressure compensation.

PRESSURE COMPENSATION

As spirometer response begins to fall at higher input frequencies, chest wall movements become translated into changes of box pressure. Since pressure leads volume oscillations, the addition of pressure to the volume signal supplements the volume amplitude and corrects for spirometer-induced phase lags (Fig. 3). Conversely, when a spirometer resonates, flow may lead box pressure, an outward displacement of the spirometer resulting in a negative box pressure. Addition of box volume and pressure signals thus restores, at least in part, a semblance of system linearity.

The common means of optimizing pressure compensation is by adjusting the box pressure gain, thus altering the signal being added to the spirometer output. The speed of the FFT and the graphic nature of the transfer function makes it a simple matter to adjust box pressure gain to obtain an optimal frequency response.

Since box pressure directly depends upon the compliance and thus volume of air in the box, it varies with subject size for a given change in lung volume (Fig. 4). Ideally, therefore, pressure compensation should be checked by the transfer function with each subject in the plethysmograph. This could be done by injecting random noise into the box by a loudspeaker, thus making rapid measurements feasible.

COHERENCE

For a transfer function to provide data of much utility, the box output must be linearily and singularly related to the input. That is, a cause and effect relationship must exist. This might not be the case if electrical or mechanical noise or extraneous signals interfere with the desired box output, or if the device creating the output signal responds in a complex manner to volume displacements. The coherence function (Michaelson, Grassman, and Peters 1975) illustrated in Fig. 5 is a way of verifying system linearity. This function, analogous to the time domain's correlation coefficient is defined as $\frac{G_{AB}^{*} \cdot G_{AB}}{G_{AA}^{*} \cdot G_{BB}}$, or as a real spectrum "power squared" ratio. Coherence for any given frequency is maximally equal to 1. If coherence drops below 0.95 at any point in the bandwidth of interest, and is not correctable, it should be recognized that the transfer junction may be inaccurate over that portion of the frequency spectrum. The act of pressure compensation can impair coherence at low but physiologically important frequencies.

EQUALIZATION

A transfer function obtained by comparing a spirometer output to an input reference signal is useful for calibrating a plethysmograph, but may not be the best way of adjusting a pressure compensation circuit. The transfer function is determined in part by the characteristics of tubing from the forcing device to the box and by the compliance of air within the box.

This compliance is in turn determined by the volume of gas within the box and by gas compressibility. Only after the input signal has been conditioned by these factors do the spirometer characteristics come to play. The purpose of pressure compensaton is to optimize spirometer response by the judicious addition of a box pressure signal to the spirometer output. Equalization provides a means for removing from the final transfer function the influence of tubing and box volume. This is accomplished by closing off or locking the spirometer to convert the volume box to a pressure box. A transfer function relating box pressure to driving pressure can then be obtained and stored. With the spirometer restored to full function, a whole system transfer function can then be obtained. The whole system TF can then undergo complex division by the pressure box TF, an act which divides the magnitude of the whole function by the pressure box function, while simultaneously subtracting the respective phase spectra. As seen in Fig. 6 the result more clearly defines the characteristics of the spirometer and the compensation circuit.

RECOMMENDED PROCEDURES

The following section describes procedures for initial plethysmograph set-up, damping, and compensation.

1) Connect to a port in the plethysmograph, and as close to the box as possible, a forcing device, either a sine-wave pump or loudspeaker.

2) Two signals must be available for processing by the FFT, a reference signal emanating from the forcing device and the plethysmograph spirometer signal.

3) The mode of spectral averaging required for the transfer function depends on the forcing function, with summation averaging for random noise or impulses, and sweep averaging for swept sine inputs.

4) Obtain a transfer function from the undamped spirometer and note resonance peaks and high frequency fall-off of amplitude, as well as phase changes. The transfer function will be linearized by the use of pressure compensation and damping, in that order.

5) Increase the gain on the box pressure signal until the combined signal (spirometer + box pressure) yields a fairly linear transfer function with minimal phase lags (Figs. 2 and 3).

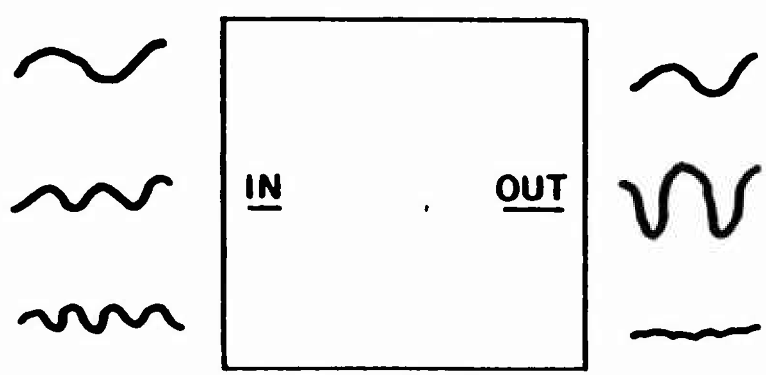
6) Add damping material (cloth, wire screening) between the plethysmograph and spirometer to increase linearity of the transfer function. Do not over-damp or high frequency response and low frequency coherence may worsen.

LINEARITY DESCRIPTIONS

In describing the change in amplitude response with frequency (f), at least two options are available. The simplest is to describe the percentage change in amplitude over a given frequency range, say 5% from 1-20 Hz. However, the fall-off of amplitude with frequency is often logarithmic, especially prior to pressure compensation, and more information may be provided by a description of "decibel drop per octave." If the amplitude of a volume output signal corresponding to a fixed amplitude, frequency swept input signal varied from 10 volts at 1 Hz to 8.1 v at 2 Hz, 5.4 v at 8 Hz, and 3.5 v at 32 Hz, the amplitude drop-off could be described by a logarithmic equation of the form $y = \ln f^{-0.3}$ or more simply as a 0.89 db/octave decay (an octave being a doubling of frequency; 5 octaves covering the frequency range from 1 to 32 Hz). A more rapid amplitude decay from 10 v at 1 Hz to 2.3 v at 8 Hz and 0.9 v at 32 Hz would represent a 2.1 db/octave drop off ($y = \ln f^{-0.7}$).

SUMMARY

The Fast Fourier transform provides a rapid means for determining tranfer functions of volume plethsymographs. These functions describe in a complete and easily interpreted format just what the box-spirometer-amplifier system is doing to the signal of interest, usually respiratory volume. It thereby is useful in adjusting pressure compensation circuits which in turn allow the useful frequency range of the plethysmograph to be extended.



TRANSFER FUNCTION

MAGNITUDE	PHASE LAG (ϕ)
1	0°
2	90°
0	180°

Fig. 1. The transfer function describes how the output of a transducer system relates to the input in amplitude and phase over a range of input frequencies.

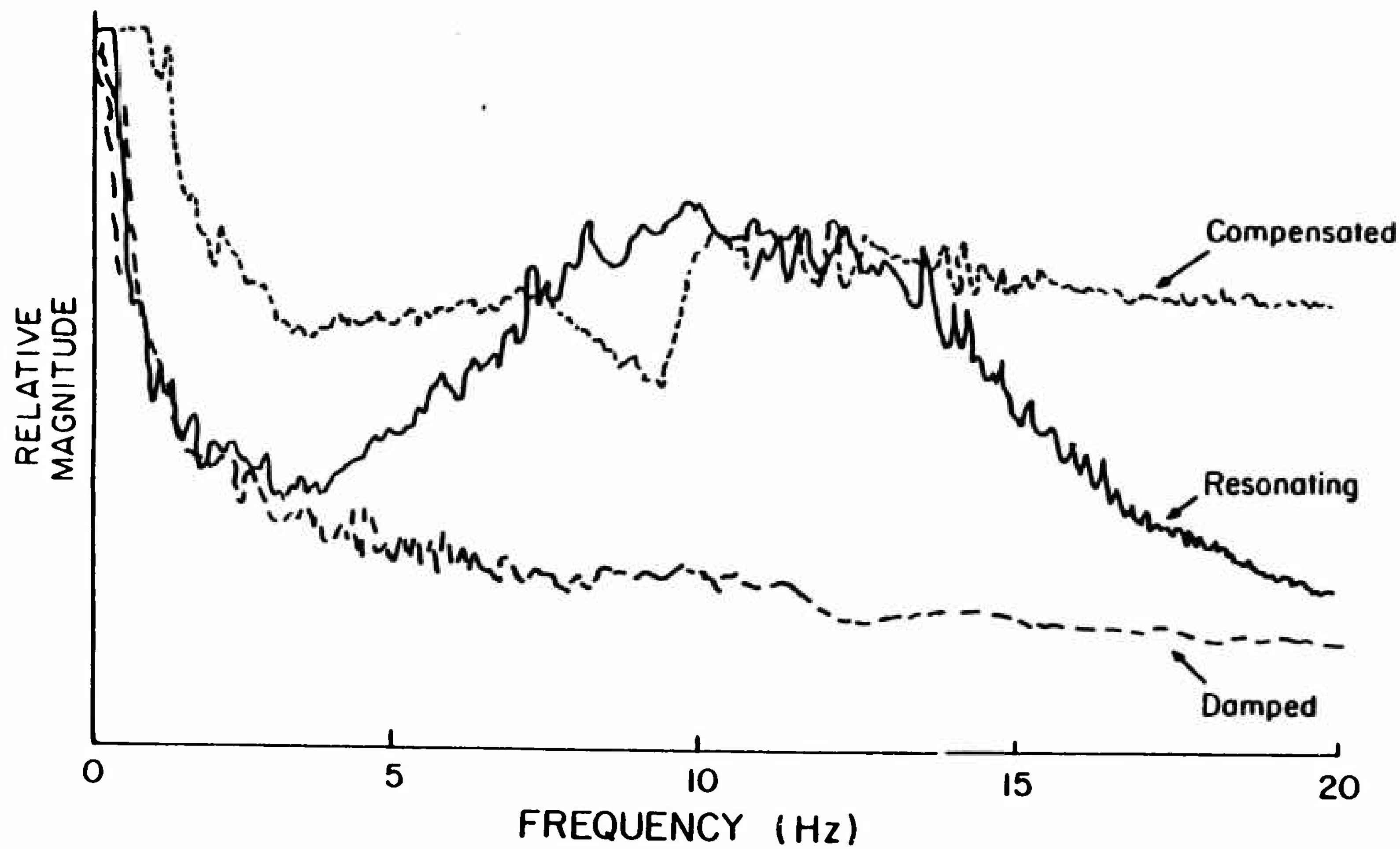


Fig. 2. The transfer function (amplitude response only) of a plethysmograph with an undamped rolling seal spirometer (solid line), the same spirometer with damping but no pressure compensation (dashed line), and with compensation but no damping.

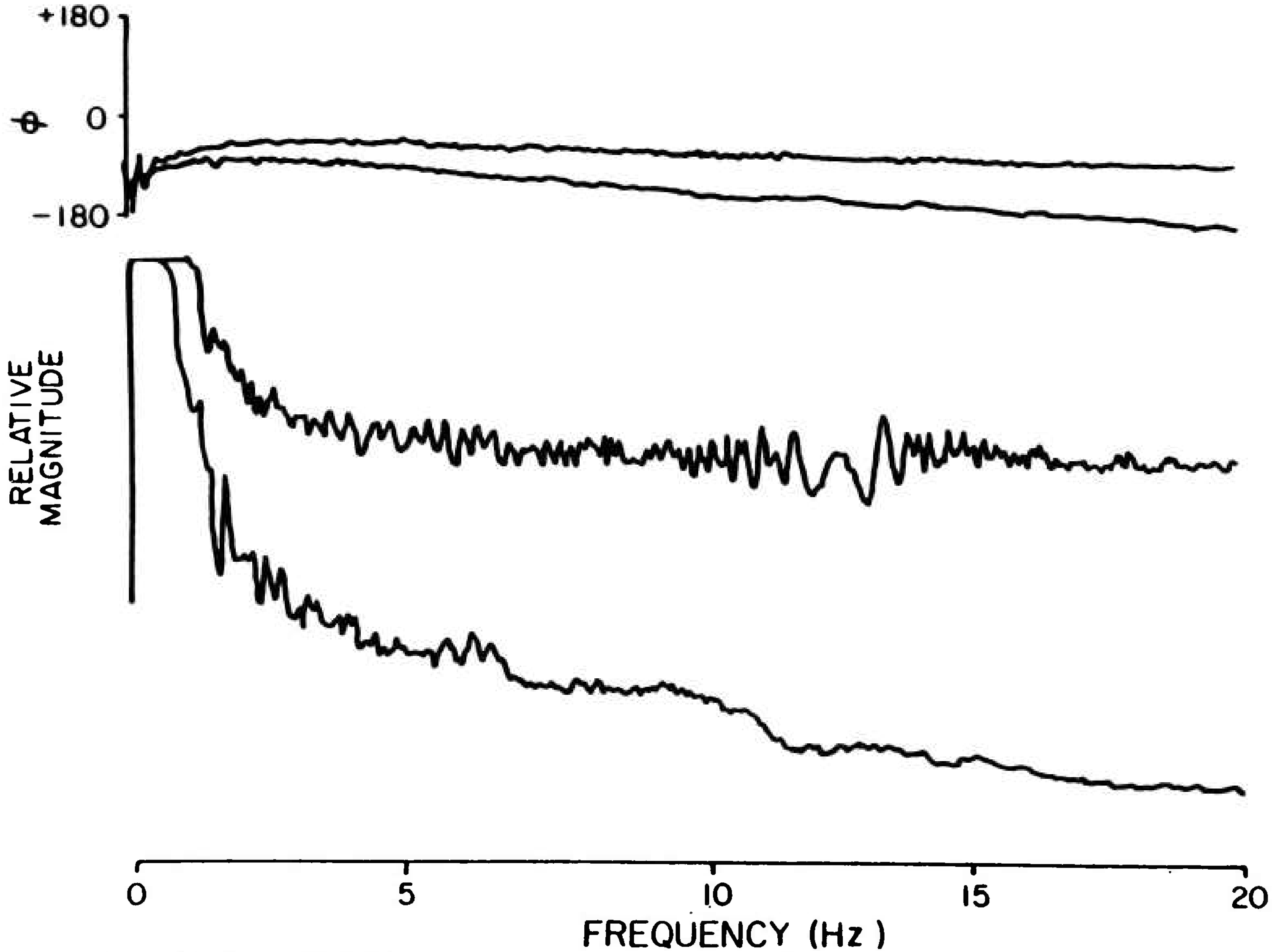


Fig. 3. The transfer function of a damped volume plethysmograph with and without pressure compensation over a frequency range from 0-20 Hz. Compensation resulted in an 8.6 db improvement in amplitude response and a reduction in phase lag at 20 Hz.

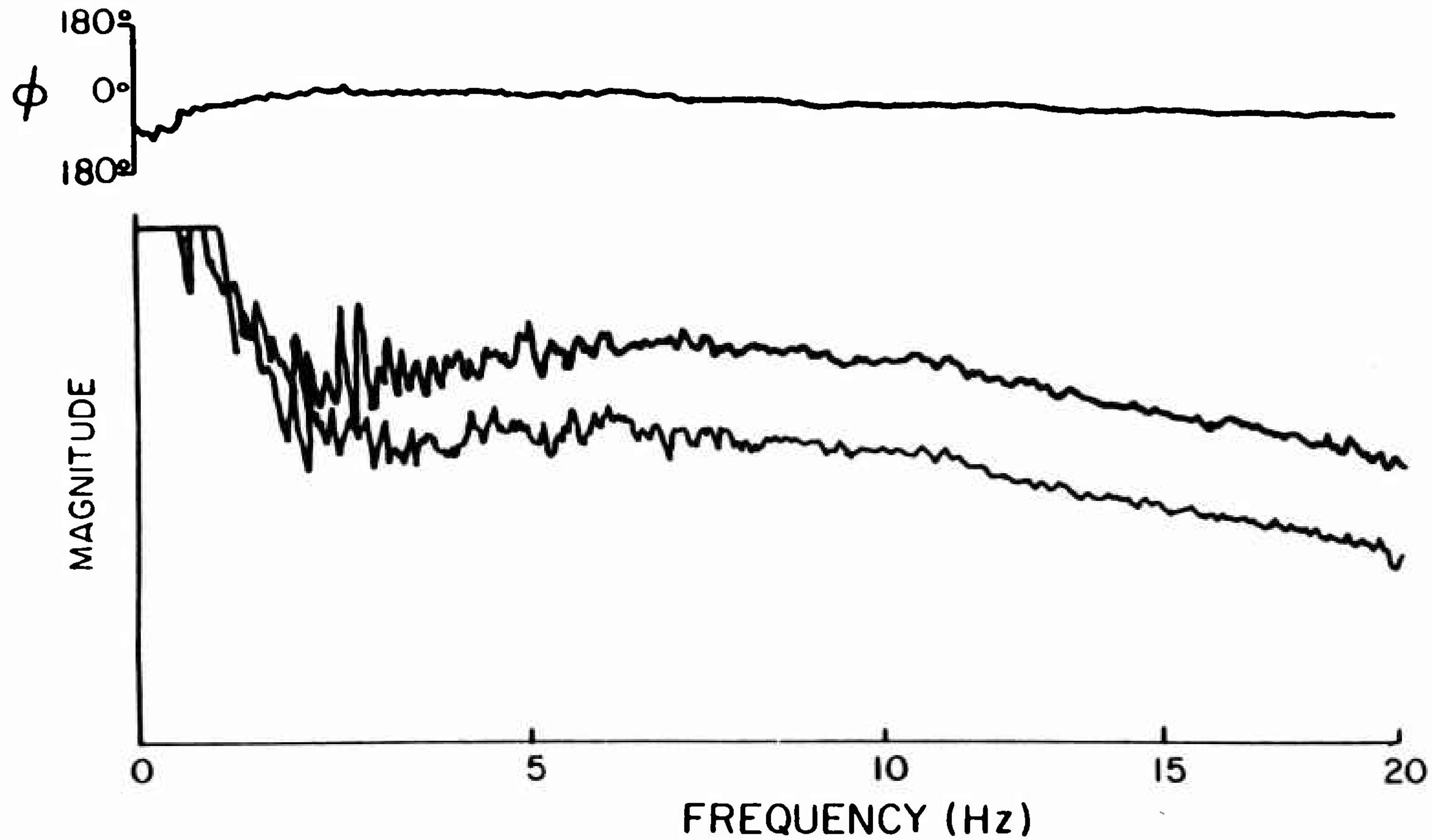


Fig. 4. The dependence of pressure compensation on plethysmograph air volume. Amplitude: The lower curve was obtained in an empty plethysmograph, while a closed bottle similar in volume to a dog, was used in the upper curve. Phase: Air volume had no effect on the phase portion of the transfer function.

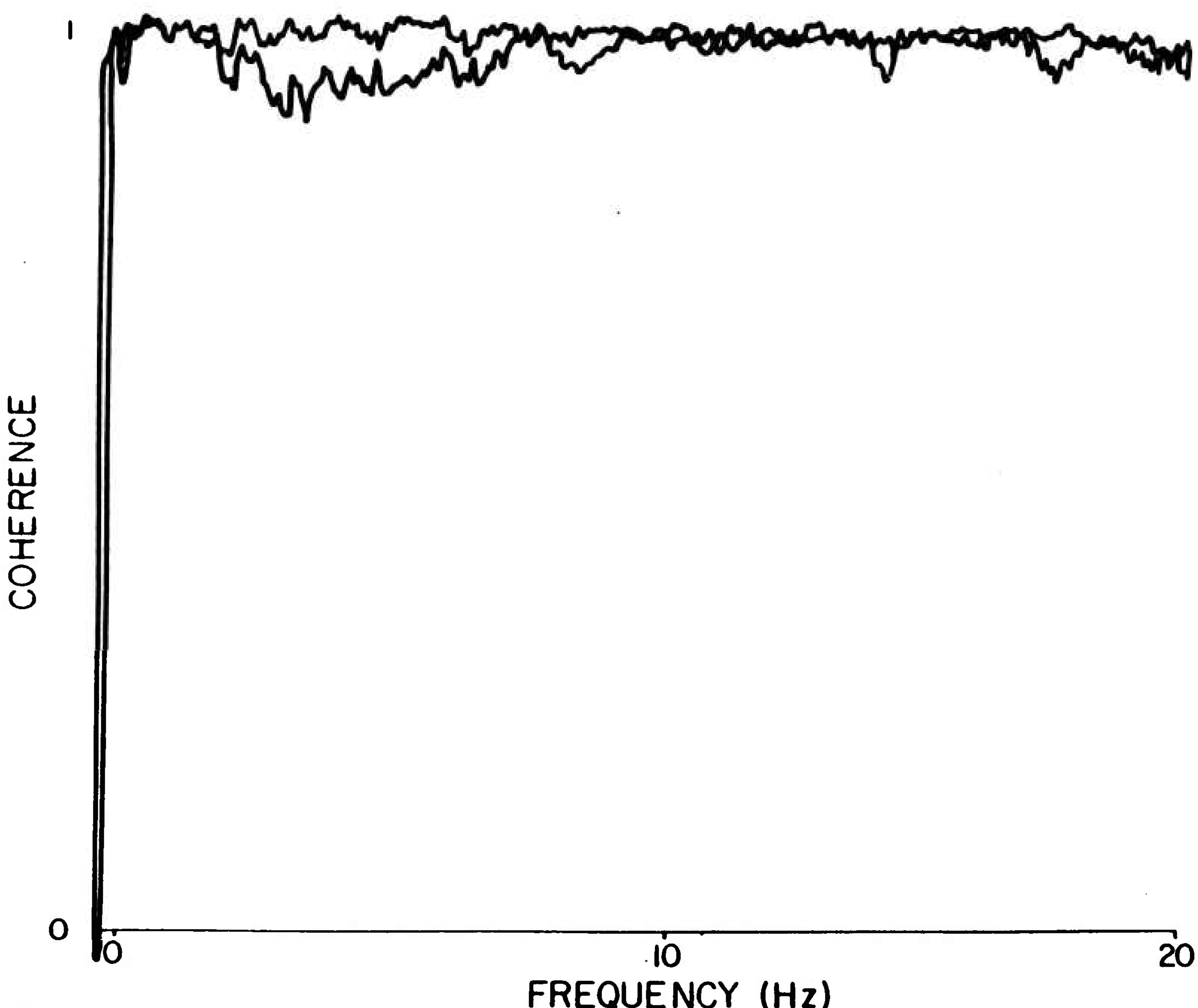


Fig. 5. Coherence functions for a typical volume plethysmograph with (lower line) and without pressure compensation. In this example, pressure compensation resulted in a drop in coherence below 0.95 over a range from 2.4-7.5 Hz. Over that range therefore the transfer function may not provide as accurate a description of system response as at other frequencies.

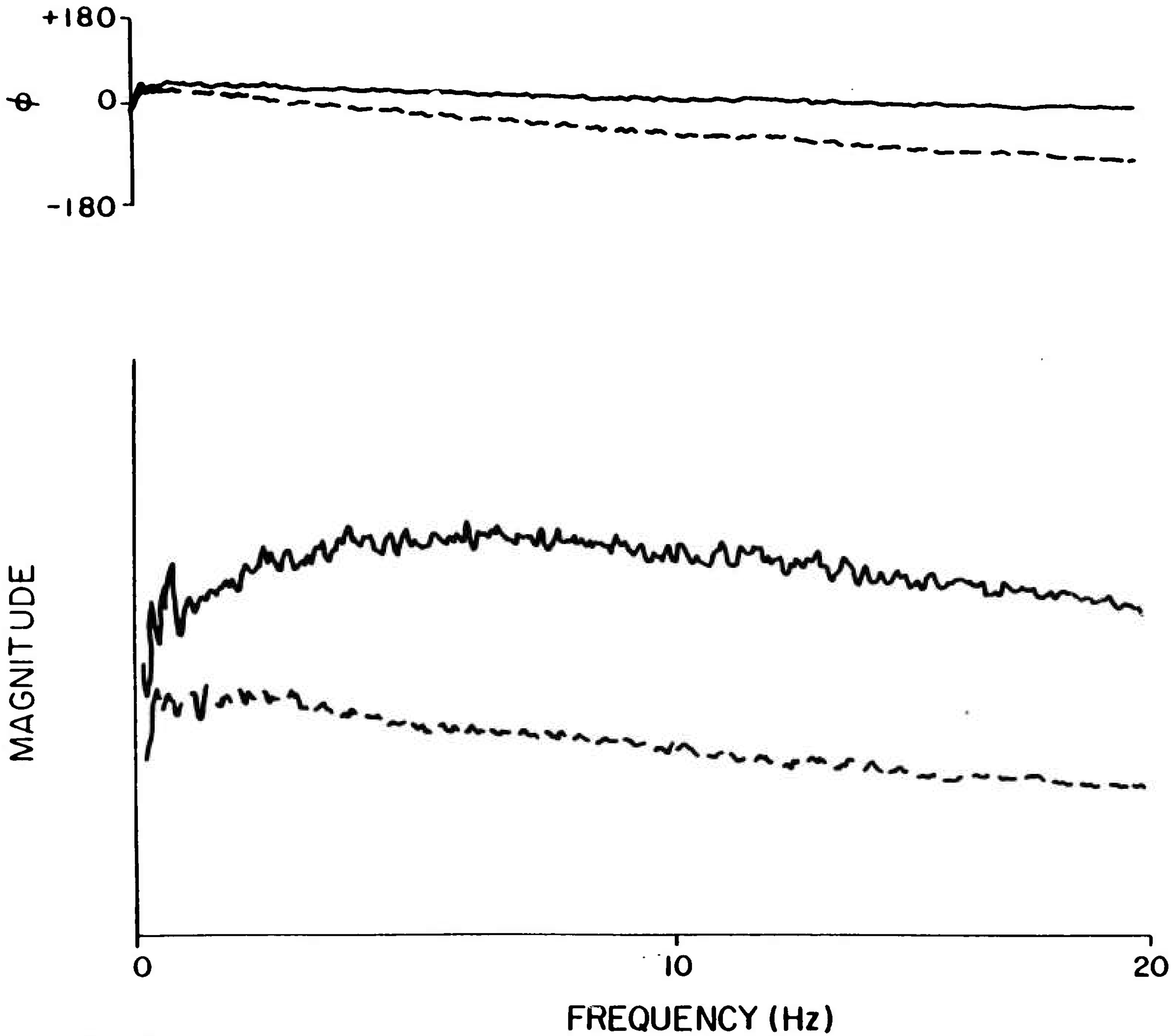


Fig. 6. The effect of transfer function equalization. By isolating the spirometer response from the whole system response. an overcompensation (solid line) may be more readily seen.

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